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State-of-the-art of transmission expansion planning: Comprehensive review

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ABSTRACT

In recent years, a large number of research works have been carried out in transmission expansion planning (TEP) field. TEP problem has been investigated with different views, methods, constraints, and objectives. Thus, it is required to evaluate and to overview the proposed works. This paper will review TEP problem from different aspects such as modeling, solving methods, reliability, distributed generation, electricity market, uncertainties, line congestion and reactive power planning. The review results provide a comprehensive background to find out the further works in this field.

Contents

1. Introduction

Optimal network expansion has always been one of the most important issues in power system planning. Power system expansion can be carried out in generation, transmission or distribution sector. In this regard, transmission expansion planning (TEP) has been widely investigated as a non-detachable part of long term

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power system planning. In TEP, the objective is to expand the existing power system to serve the growing demand in the future. The TEP denotes where, when and how many new lines should be installed in power system to support the demand of the network. Since TEP problem is a nonlinear mixed integer constrained programming, it can be analyzed from different views and aspects which can be categorized as follows:

(i) Modeling [1–6]
(ii) Solving method [7–52]
(iii) Reliability [2,6,25,31,53,54]
(iv) Line congestion [13,15,29,48,55,56]
(v) Reactive power planning [2,3]
(vi) Electricity market [2,7,13,20,43,44,49,55,57–65]
(vii) Uncertainty [14,31,37,63,65–68]
(viii) Considering the distributed generation [69–71]
(ix) The view of time horizon [72,73]
(x) Environmental impact [74]
(xi) Flexible AC Transmission System (FACTS) devices [75–77]
(xii) Coordinated TEP and GEP [6,14,16,78,79]
(xiii) Integration of wind farms in TEP problem [67,80–82]
(xiv) Security constrained TEP problem [83–87].

In this paper, a complete and comprehensive overview of the TEP problem is presented with consideration of the proposed aspects. Although TEP review has already been investigated in [72,73], the current paper is more comprehensive and complete. There are different subjects that either have not been investigated by these references or have been reviewed very briefly; while these issues will be thoroughly reviewed in this paper. These issues are TEP modeling such as AC and DC modeling with their advantages and disadvantages, the effect of the line congestion on TEP, uncertainty in TEP and the effect of the environmental emissions on TEP. Also, there are some new issues in TEP problem which have been discussed in recent years such as the effect of distributed generations on TEP, the application of FACTS devices in TEP and coordinated TEP-GEP (generation expansion planning). These subjects have not been investigated in any paper, while this paper presents a comprehensive review of the above-mentioned issues with studying their different aspects.

It is worth mentioning that for reviewing articles, there are many different criteria for choosing references such as the year of the publication, journal and conference categories, the subject and novelty of papers. In this paper, we have managed our review based on the subject and novelty of papers. Then, the papers were categorized and managed based on their subjects such as modeling, solving methods, reliability, electricity market, uncertainties.

Apart from this introductory, this paper is categorized as following sections: the TEP problem is described in Section 2 and then the proposed items are studied in Section 3. In this section, the reason for considering each item is reviewed and the proper papers are cited. Eventually in Section 4, a comparative review between some cited papers is presented.

2. TEP overview

From view of mathematical modeling, TEP is a mixed integer constrained nonlinear optimization programming. The classical optimization problems, like TEP, generally contain two parts as objective function and constraints. The flexibility of TEP problem is changed by considering different objective functions and constraints. Different objective functions have been evaluated in the TEP such as line cost, reliability cost, congestion cost, electricity market costs etc. TEP problem constraints can also be categorized into two sections: mandatory constraints and optional constraints. Mandatory constraints are the power system operational constraints such as the limits of the generator output power, the limits of voltage levels and the limits of transmission power in lines. The optional constraints are the extra constraints such as the limits of the investment, the reliability and security limits and environmental impact limits. Mandatory constraints should be included in the TEP problem, but optional constraints are only used in order to have more flexibility and they are not mandatory. Based on the proposed descriptions, the TEP problem optimization can be managed as follows:

Min *Objective function* subject to *Mandatory constraints* and *Optional constraints*

3. TEP problem evaluation

As referred before, TEP problem has been performed with different methods and models. In this section, the relevant methods are evaluated and a proper citation is also provided.

3.1. TEP from view of modeling

There are two general modeling for TEP problem which are AC model [1,2,7–10,17–21,23,24,36–42,45–48,57–67,88] and DC model [3–6,11,13–16,22,25,27,29–35,43,44,49–51,55,56,68]. AC model is a complete and practical one, but it is complex. The DC model is simple, but it contains simplifications. Advantages and disadvantages of these models can be concluded as follows:

DC model disadvantages

(i) In DC modeling, the reactive power cannot be incorporated.
(ii) The resulted plan from DC model should be reinforced when the AC operation is considered.
(iii) It is difficult to consider power losses in DC model.

AC model advantages

(i) Considering reactive power and in planning.
(ii) Reactive power planning can be associated with TEP to achieve less new lines.
(iii) Power losses can be completely included.
(iv) The other components such as FACTS devices can be included.
(v) The other types of studies such as voltage stability can be carried out.

AC model disadvantages

(i) AC model leads to a large and complex nonlinear programming problem.
(ii) An efficient optimization technique is required to solve the AC model.
(iii) Handling disconnected systems, a common situation in the initial phase of transmission planning, when generators and loads have not yet been electrically connected to the network.

3.2. TEP from view of solving method

In TEP problem, the planning objectives are in conflict with each other and this is an important challenge in TEP. In traditional planning, the objective of TEP is to minimize the investment cost. However, in advanced planning, the planning should be carried out with different objectives such as:

(i) Facilitating competition between market stockholders [7]
(ii) Providing nondiscriminatory and competitive environment for all stockholders [43]

(iii) Mitigating transmission congestion [13,15,29,48,55,56]
(iv) Minimizing investment cost [1–69,88]
(v) Minimizing risks [31]
(vi) Reliability and security improvement [2,6,25,31,53,54]
(vii) Considering distributed generation [69–71]
(viii) Minimizing environmental impact [74]

The proposed objectives are often in conflict and cannot be always satisfied at the same time. Thus, TEP problem becomes a multi objective optimization problem which cannot be solved effectively by traditional planning methods. In this regard, many different methods have been carried out to solve the proposed multi objective optimization problem. These solving methods can be divided into two main methods: mathematical and Meta-heuristic optimization methods. These methods can be categorized in details as follows:

Mathematical optimization methods

(i) Linear programming [7–9], nonlinear programming [10,11] and mixed integer programming [12]
(ii) Bender's decomposition [13–16] and branch-bound method [17,18,20]
(iii) Game theory [19,21]
(iv) Heuristic algorithm based on sensitivity index [1,22]
(v) Hierarchical decomposition [23]
(vi) Dynamic programming [24]

Meta-heuristic optimization methods

(i) Ant colony [25]
(ii) Artificial immune system [26]
(iii) Artificial neural networks [27]
(iv) Bee algorithm [28] and Chaos [29]
(v) Differential evolution [30,31]
(vi) Expert system [32]
(vii) Frog leaping algorithm [33]
(viii) Fuzzy [34]
(ix) Genetic algorithms [35–39], decimal coded genetic algorithms [40,41], real coded genetic algorithms [3], hybrid genetic algorithms with fuzzy [42] and non-dominated sorting genetic algorithm [43,44]
(x) Greedy randomized search [45]
(xi) Harmony search [46], PSO [47,48], search based algorithm (Grid search algorithm) [49]
(xii) Simulated annealing [50] and tabu search [51,52]

It is seen that both methods (mathematic and heuristic) have been widely used to solve TEP optimization problem. By reviewing the papers, advantages and disadvantages of these methods can be concluded as follows;

Advantages of mathematical methods

(i) The optimal solution is usually accurate and solving time is low.
(ii) Suitable convergence is obtained.

Disadvantages of mathematical methods

(i) Converting power system equations into optimization programming model is difficult and troublesome and it is more complicated in large scale power systems.
(ii) In order to insert a new constraint, the model should be rearranged and new equations should be included.
(iii) In this model, power system model is converted into a set of linear or nonlinear equations. Thus, the static studies can be only used and dynamical studies such as stability analysis cannot be performed.

Advantages of heuristic methods

(i) These methods are easy to use and very straightforward.
(ii) In these methods, it is not required to covert power system model into an optimization programming set. The power system analysis (such as load flow, optimal load flow or stability analysis) can be carried out in a power system analyzer package (such as DigSILENT power factory) and then the output responses are fed into optimization method. In fact, these methods only need the output responses to solve the problem.
(iii) Implementing these methods is easy and dynamical studies such as stability analysis can be carried out.

Disadvantages of heuristic methods

(i) The optimal solution is associated with approximations and simulation time is usually high.
(ii) It is possible to fall into local minima instead of global minima.
(iii) The possibility of the divergence is more than the mathematical methods.

3.3. TEP associated with reliability

Reasonability of a typical power system planning is evaluated in two macro and micro stages. The macro stage is related to studying the planning from the view of the strategic policy, but the micro stage is related to studying the planning from the view of engineering feasibility. Adequacy, security and reliability analysis are related to the macro stage and technical analysis such as fault analysis and stability analysis are related to the micro stage. The conventional procedure for power system planning is shown in Fig. 1. It is seen that the reliability and adequacy analyses are carried out before stability and fault analyses. Thus, any power system planning such as TEP should be associated with reliability/security analysis. On the other hand, reliability evaluation should be incorporated in any long term planning such as TEP; otherwise, there is no guarantee of a trustworthy supply for demands. However, an expanded plan should satisfy reliability criterion and ensure reliability requirements. In TEP problem, reliability has been investigated as different forms. The reliability of the system can be included as a constraint or as a part of objective function. The most commonly reliability indexes are used to assess the system reliability. These indexes are as follows:

(i) Loss of load expectation (LOLE) [2]
(ii) Hierarchical reliability assessment [6]
(iii) Loss of load cost (LOLC) [25]
(iv) Energy expected not supplied (EENS) [31]
(v) Reliability improvement index [53]

Also, the security can be included in TEP problem. The security analysis is to ensure the performance requirements under one contingency. Contingency n-1 [5,15,17] and deliberate outages [54] are often used as a constraint in TEP problem.

3.4. TEP associated with line congestion

In the deregulated electricity market, transmission congestion is an important issue that needs to be incorporated in power system operation and network expansion planning. TEP associated with transmission congestion is handled with different objectives such as considering the operation cost due to congestion [13], considering the available transfer capability [15], considering

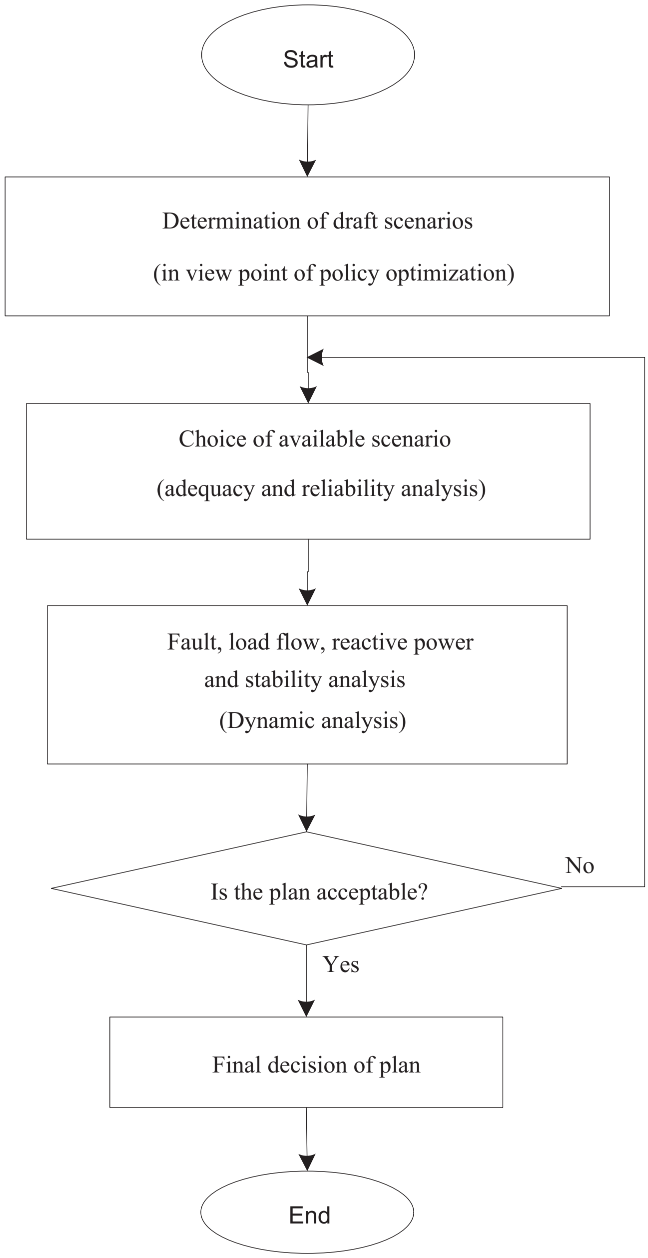

Fig. 1. Traditional work procedure for power system planning [17].

transmission surplus capacity [29], considering transmission line loading [48], and considering congestion management in a practical case study TEP [55] and enhancing transmission system capability and having the congestion alleviated using TEP [56]. However, congestion studies are associated with TEP problem and researchers are interested in this topic [57–59,68,69].

3.5. *TEP associated with reactive power planning*

In practical power systems, the reactive loads are supplied via generators. In this case, the reactive power is transferred through transmission lines and transferring such an amount of reactive power may reduce the available transfer capability and this may lead to build more new transmission lines. Nevertheless, by allocating locally reactive sources close to the load centers, it is possible to supply reactive demands and the capacity of transmission lines is thereby increased and also the power losses are reduced. Therefore, TEP problem should be associated with reactive power planning and otherwise, the TEP leads to build more new lines [2,3].

3.6. *TEP in deregulated electricity market*

With restructuring the electricity markets, transmission lines have attracted more attention from the view of stockholders, participants, independent system operator (ISO) and customers [57,58]. Traditional TEP is no longer viable in a restructured power system. An optimal TEP scheme in this new environment requires new methods and tools. In regulated electricity markets, the objective is to minimize the investment costs of new transmission lines, subject to operational constraints such as demand satisfaction. However, in deregulated electricity markets, the main objective of the TEP is to provide a non-discriminatory and competitive environment for all stakeholders by considering power system reliability. Fig. 2 shows the procedure of TEP problem in regulated and deregulated electricity markets respectively [58]. Fig. 2A shows that TEP problem in traditional systems is carried out to minimize the cost and consideration of system operational constraints. In this environment the procedure has a vertical order. But, in deregulated electricity market as depicted in Fig. 2B, the order is not vertical and feedback signals are introduced. In deregulated environments, TEP problem has been investigated with different viewpoints such as considering nodal prices [2], load curtailment cost [7], transmission congestion cost [13,43,44,57] and social welfare [20,59] and minimizing market risk [60]. Also, TEP problem in an imperfect deregulated market in which only the generator sector is deregulated has been reported [49]. A European case study of TEP is reported in [55]. This paper presents TEP in a trilateral electricity market in Europe with the allocation of the financial transmission right to investors. TEP problem in a pool market which aims to select the most effective subset of lines has been reported in [61] and TEP problem with considering the demand response in deregulated market is reported in [62].

3.7. *Considering uncertainty in TEP*

Power system uncertainties should be incorporated in any power system planning similar with TEP. A comparison between deterministic and stochastic models in TEP has been reported in [66]. This paper shows that the TEP plans which consider uncertainty perform better than plans with deterministic models. Also, the uncertainty in deregulated market is more than the regulated electricity markets, because in regulated markets, the planner can obtain all information of the system, but in the deregulated environment, some information about Generation, transmission and distribution companies are confidential and cannot be obtained by the planner. Some generic uncertainties are as follows:

(i) Load and price forecast uncertainty [14,31,37,63–65,68,88]
(ii) Availability of power system components [14]
(iii) Uncertainties due to simplification in modeling and simulation [31]
(iv) Market uncertainties [37,63–65,88], Energy and its risk [63], Fuel availability and cost [88]
(v) New technologies of generation such as wind farms and photo voltaic units [67]
(vi) Government and political policies [63–65,88] and environmental aspects and their cost [74]

With regard to the proposed uncertainties, the TEP is often faced with the risk. Thus, new methods should be incorporated to

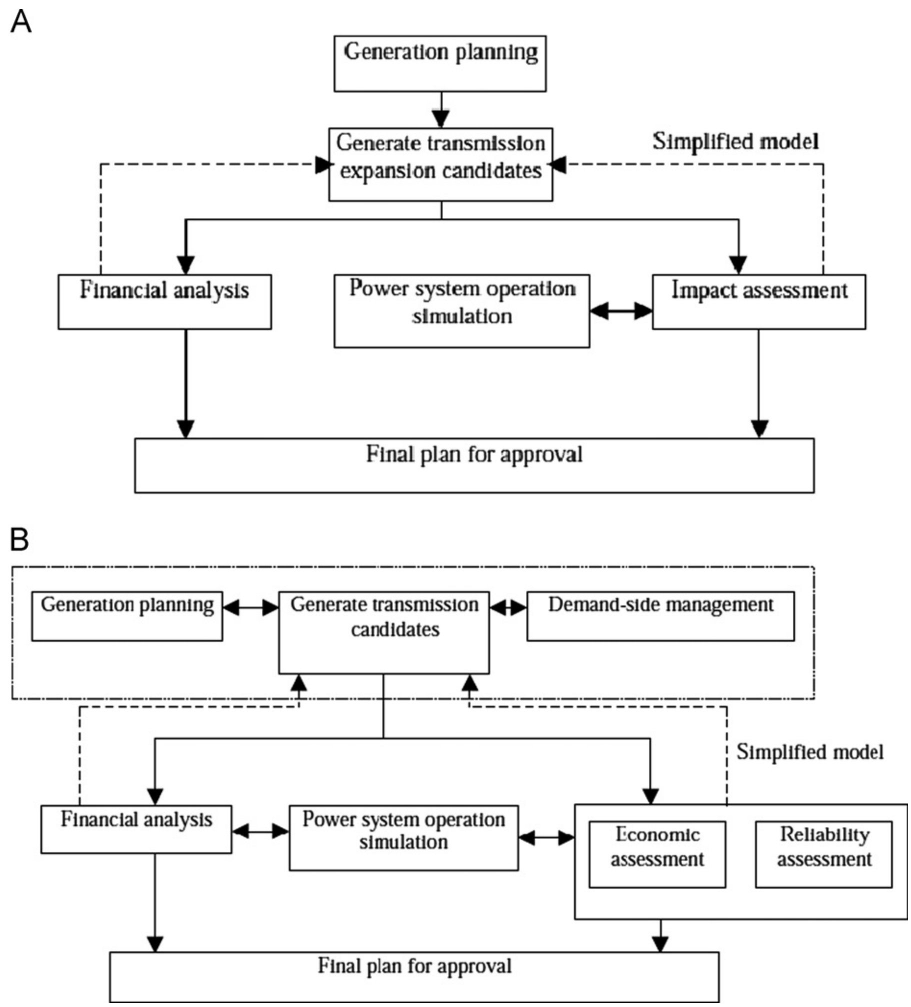

Fig. 2. Transmission expansion planning procedure in power system [58]. (A): traditional environment. (B): deregulated environment.

deal with uncertainties. The most commonly used methods to deal with uncertainties are:

(i) Mathematical-statistical model [31,67]
(ii) Monte-Carlo Simulation (MCS) [14,37,63,64,68]

Mathematical method uses probabilistic models for considering uncertainty. But, MCS is a numerical method based on the iterations. Mathematical method takes less computation time than MCS, but MCS is easy to be implemented. Both methods have been widely used to deal with uncertainties in the TEP problem [67,68].

3.8. TEP problem with consideration of renewable distributed generation

In recent years, distributed generations (DG) have attracted more attention in power systems. Distributed generation units mainly use the renewable energy resources such as wind, solar, hydrogen, geothermal, bio energy etc. The classical centralized generation model is faced with several problems such as high cost, long transmission system, environmental effects, risk and reliability and power losses. But, DG systems are installed near the load center. This property of DG leads to have less power transmission, less losses, less cost and more reliability. However, penetration of DG will cause significant changes in the power system, and also it deeply influences the TEP. For example, DG affects on the local demands and changes local marginal prices in electricity market, or changes power losses in transmission lines. Therefore, it is required to consider the effect of DG on TEP problem [69]. The application of DG in practical TEP problems has been investigated in Australia [70] and UK [71].

3.9. TEP problem from view of time horizon

From view of time horizon, TEP problem is classified as static and dynamic planning. In static planning, time horizon is not considered and the optimal plan is determined for a single year. In other words, it is assumed that all new lines should be installed in the first year of the planning horizon. But, in dynamic planning, the years of horizon are separately studied and new lines for each year are denoted. In fact, it is assumed that each new line should be installed in its relative year of the planning horizon. It seems that the dynamic planning leads to a better and cheaper planning, but it is very complex, large and time-consuming [72].

3.10. TEP and environmental impacts

Nowadays, environmental emissions such as carbon, oxide nitrogen and natural gases are limited based on the regulation of Environmental Protection Agencies (EPA). The planners are encouraged to install renewable energies instead of conventional energies such as oil. Midwest Independent Transmission System Operator (MISO) has reported a Transmission Expansion Plan [74]. This company has considered environmental impact analysis in the TEP planning, where the environmental impacts are analyzed based on the EPA regulations.

Table 1
Outline study of the cited papers.

Ref. no	Solving method		Electricity market	Uncertainty	Reliability/ Security	Transmission congestion	Reactive power planning	DG
	Mathematical	Heuristic						
[1]	√	–	–	–	–	–	–	–
[2]	–	√	√	–	√	–	√	–
[3]	–	√	–	–	–	–	√	–
[4]	√	–	–	–	–	–	–	–
[6]	√	–	–	–	√	–	–	–
[7]	√	–	√	–	–	–	–	–
[8]	√	–	–	–	–	–	–	–
[10]	√	–	–	–	–	–	–	–
[11]	√	–	–	–	–	–	–	–
[13]	√	–	√	–	√	√	–	–
[14]	√	–	√	√	√	–	–	–
[15]	√	–	–	–	√	√	–	–
[16]	√	–	–	–	–	–	–	–
[17]	√	–	–	–	√	–	–	–
[18]	√	–	–	–	–	–	–	–
[19]	√	–	√	–	–	–	–	–
[20]	√	–	–	–	–	–	–	–
[21]	√	–	–	–	–	–	–	–
[22]	√	–	–	–	–	–	–	–
[25]	–	√	–	–	√	–	–	–
[27]	–	√	–	–	–	–	–	–
[28]	–	√	–	–	–	–	–	–
[29]	–	√	–	–	–	√	–	–
[30]	–	√	–	–	–	–	–	–
[31]	–	√	–	√	√	–	–	–
[33]	–	√	–	–	–	–	–	–
[34]	–	√	–	–	–	–	–	–
[35]	–	√	–	–	–	–	–	–
[36]	–	√	–	–	–	––	–	–
[37]	–	√	–	√	–	–	–	–
[38]	–	√	–	–	–	–	–	–
[39]	–	√	–	–	–	–	–	–
[40]	–	√	–	–	–	–	–	–
[41]	–	√	–	–	–	–	–	–
[42]	–	√	–	–	–	–	–	–
[43]	–	√	√	–	–	–	–	–
[44]	–	√	√	–	–	–	–	–
[46]		√	–	–	–	–	–	–
[47]	–	√	–	–	–	–	–	–
[48]	–	√	–	–	–	√	–	–
[49]	–	√	√	–	–	–	–	–
[50]	–	√	–	–	–	–	–	–
[55]	√	–	√	–	–	√	–	–
[56]	–	√	√	–	–	√	–	–
[61]	–	√	√	–	–	–	–	–
[62]	√	–	√	–	–	–	–	–
[63]	–	√	√	√	√	–	–	–
[67]	√	–	√	√	–	–	–	–
[69]	√	–	–	√	–	√	–	–
[70]	–	√	√	√	√	–	–	√

3.11. TEP with FACTS devices

In TEP problem, network expansion is typically made by adding new transmission lines. Installing new lines increases the transmission system capacity. However, FACTS devices also can increase the transmission system capacity [75] and can be used instead of installing new lines. This issue has been investigated in [76,77].

3.12. Coordinated TEP and GEP

In real power systems, the generation and transmission sectors are not apart from each other. In this regard, transmission expansion planning can be performed associated with generation expansion planning (GEP). This coordinated TEP and GEP has recently attracted more attention. Many investigations have been carried out to perform coordinated TEP and GEP [6,14,16,78,79]. The coordinated GEP and TEP has been investigated under both regulated [6] and deregulated [14,16] electricity markets.

3.13. Integration of wind farms in TEP problem

Recently, wind farms are rapidly integrating into power systems because of their favorable characteristics. However, the wind power output is continuously changing and thus, an extra factor of uncertainty is introduced in power system operation and planning. Therefore, in power systems with wind power uncertainties, the deterministic TEP methods are not suitable and a method with considering the wind power uncertainties should be incorporated [67,80–82]. Different methods have been used to deal with wind farm uncertainties such as Monte-Carlo simulation and point estimation method [80,81].

3.14. Security constrained TEP problem

TEP problem is a very critical issue due to not only the huge investment cost involved, but also the associated security issues [87]. Security constrained transmission expansion planning has been widely investigated in recent years [83–86]. Different security constraints have been considered in TEP problem such as voltage stability margin [83], line flows and generations limitations [86], steady state voltage security [84] and security (N-1) criterion [85].

4. Comparison of researches

Table 1 shows an outline review of the cited papers. The papers are evaluated form different aspects and a complete comparison is carried out. It is seen that the researchers have focused on the market type, uncertainty, reliability and congestion. It seems that the most favorite aspect of the TEP problem is to study TEP in a deregulated electricity market considering reliability.

5. Conclusions

TEP problem reviewed with the consideration of different aspects in this paper. The recently published papers evaluated from different views. The proposed cited papers show that TEP problem is required to serve the demand in the future. Besides, in order to achieve a better and flexible planning, the TEP problem should be studied with considering different aspects such as uncertainty, market concepts, congestion management, reactive power planning, distributed generation. However, there is not a unique methodology for TEP planning and it differs from one system to another. Studying the TEP problem in this paper opens the door for further works in this field. In general, the TEP models developed so far have one or more of the following drawbacks:

(i) Distributed generation has not been properly studied.
(ii) Reactive power planning has not been thoroughly studied.
(iii) Uncertainties associated with new generation technologies such as wind farms and photo voltaic have not been properly investigated.
(iv) Hydro power stations and related effects have not been properly included.
(v) Coordinated TEP with generation expansion planning (GEP) have attracted limited attention.
(vi) Considering FACTS devices in TEP has not been properly investigated

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